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AFRPL-TR-68-103

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(U) ADAPTATION OF A TECHNIQUE FOR PREDICTING LARGE SOLID ROCKET MOTOR SPECIFIC IMPULSE FROM DATA OBTAINED IN MICROMOTORS

JAMES E. VINT, CAPTAIN, USAF

TECHNICAL REPORT NUMBER AFRPL-TR-68-103

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ADAPTATION OF A TECHNIQUE FOR PREDICTING LARGE SOLID ROCKET MOTOR SPECIFIC IMPULSE FROM DATA OBTAINED IN MICROMOTORS (U)

James E. Vint, Capt, USAF

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FOREWORD

This report describes work covered under Project 314804ACJ, for the period July 1965 to May 1968. The project engineer was James E. Vint, Captain, USAF.

The author wishes to express thanks to Captain F. Warren Villa-escusa, U. S. Air Force Academy, who initiated this program while at the Air Force Rocket Propulsion Laboratory, and did much of the early ballistic firing and data interpretation. Appreciation is also extended to Mr. P. H. Morosky, the data analyst, and Mr. E. L. LaRue and Mr. G. Timer, foremen on the program, and all the members of the Propellant Evaluation Facility and data acquisition crew for their dedication and untiring efforts in supporting the program.

This report has been reviewed and approved.

Elwood M. Douthett

ELWOOD M. DOUTHETT
Colonel, USAF
Commander, Air Force Rocket Propulsion Laboratory

UNCLASSIFIED ABSTRACT

A technique developed by the Rohm and Haas Company for specific impulse scaling has been adapted for use at the Air Force Rocket Propulsion Laboratory. The purpose of this technique is to predict specific impulse in large solid rocket motors based on data obtained in micromotors. As little as 2 pounds of propellant are required to obtain the data from which the prediction is made. The technique has been checked with a composite-modified-double-base propellant and a polybutadiene composite propellant. Within the limitations described, this technique can provide useful information concerning performance of a propellant in a large solid motor. Predictions, based on data obtained in micromotors, were within 0.6% of the delivered impulse in 6-pound motors and 70-pound BATES motors.

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FIGURES

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SYMBOLS AND DEFINITIONS

A	Area of exposed internal motor hardware, in^2.
C_{pg}	Specific heat of gaseous propellant combustion products, $\frac{BTU}{lbm^{o}R}$
C_{ps}	Specific heat of solid propellant combustion products, $\frac{BTU}{lbm^{o}R}$
I^{o}_{1000}	Specific impulse corrected to 1000-psig chamber pressure, optimum expansion ratio at sea level (14.7 psia) ambient pressure, and zero degree angle of divergence, lbf-sec/lbm.
g_o	Mass conversion factor, 32.174 lbm-ft/lbf-sec^2.
J	Energy conversion factor, 778.16 ft-lbf/BTU.
m	Propellant weight, lbm.
$\dot{m}$	Mass flow rate of propellant combustion products, lbm/sec.
$\dot{m}_g$	Mass flow rate of gaseous propellant combustion products, lbm/sec.
$\dot{m}_s$	Mass flow rate of solid propellant combustion products, lbm/sec.
N	Norris number, an experimentally determined effective solid-phase particle diameter, microns.
q	Effective heat flux, BTU/sec-ft^2.
Q	Total heat lost to motor hardware during a test firing, BTU.
Δ	Fractional velocity lag.
σ	Standard deviation.

SECTION I

INTRODUCTION

(U) In July 1965, a checkout of the Rohm and Haas Company specific impulse scaling program[1] was started at the Air Force Rocket Propulsion Laboratory, (within the Exploratory Evaluation Branch of the Propellant Division,) with the aim of using this technique to predict the performance of candidate propellant ingredients in large solid rocket motors. This technique was found to provide a good prediction of performance in large motors of the two propellants tested.

(U) Initially, data were obtained from 60 firings. These data, however, did not correlate with the Rohm and Haas results. This discrepancy was eventually traced to the placement of pressure transducers relative to the thrust axis of the motor.

(C) The composite-modified-double-base propellant used in this series was:

RH-P-112

Aluminum	15.0%
Ammonium Perchlorate	30.0%
Triethylene glycol dinitrate	37.3%
Ball Powder	16.7%
Resorcincl	1.0%

The composite propellant was:

TP-H-1011

Aluminum	16.0%
Ammonium Perchlorate	70.0%
PBAN	14.0%

SECTION II

MATERIALS AND METHODS

(U) The Rohm and Haas scaling program makes use of ballistic data from three sizes of micromotors to predict specific impulse in larger motors. The technique was developed by Rohm and Haas Company, Redstone Arsenal Research Division, Huntsville, Alabama. The dimensions of these motors are listed in Table I. In all motors, the port is cylindrical.

(U) Table I. Dimensions of Micromotors

Designation	Inside Diameter	Propellant Grain Dimensions (Nominal)		
		Port Diameter	Length	Weight
.75C. 50-1. 5	0. 75 in.	0. 50 in.	1. 5 in.	10 grams
.75C. 50-3. 5	0. 75 in.	0. 50 in.	3. 5 in.	22 grams
2C1. 5-4	2. 00 in.	1. 50 in.	4. 0 in.	145 grams

Figure 1 depicts these motors.

(U) The first and second motors listed above have the same diameters, but differ in length by a factor of slightly more than two, while the second and third configurations, considered as a pair, are nearly the same length but differ in diameter by a factor of slightly more than two. The selection of motors with these characteristics is based on the following assumptions.

(U) The motors with the same diameter, differing in length, will have similar two-phase-flow losses but significantly different heat losses, while the constant-length, different-diameter motors will have practically the same heat loss per unit mass, but will differ significantly in two-phase-flow losses[2]. No attempts were made to measure heat losses or actual

Figure 1. Motors Currently Used at the Propellant Evaluation Facility. From left - 6C5-11.4, 2C1.5-4, .75C.50-3.5, and .75C.50-1.5.

particle sizes. The intent of this effort was to determine the usefulness of the Rohm and Haas scaling program. Therefore, the same assumptions used by Rohm and Haas were used in this effort. The objective of this technique was to predict large motor specific impulse using a small quantity of propellant without actually measuring heat losses or particle size.

(U) Design of the nozzles in each motor configuration was the same, with a 45° convergence half-angle and a 15° divergence half-angle.

(U) The motors were fired in a nozzle-up position with a load cell between the head end of the motor and a concrete pad. Originally, pressure transducers were attached to the firing head (Figure 2), which was used to hold the motor together and also to attach the motor to the load cell. This arrangement was discovered to be the reason for the discrepancy in data correlation in the case of the 10- and 22-gram motors.

(U) The transducers in the two smaller motors were apparently moving upward in relation to the motor as the motor fired, and this upward movement did not have time to stabilize before the firing ended. This phenomenon produced a reduction in force exerted on the load cell. The result was a specific impulse 4 to 9 seconds lower than the values reported by Rohm and Haas Company, for the same propellant in the same motor. This firing head was replaced by a different design (Figure 3), which is used by Rohm and Haas. A head of similar design was fabricated for the 2C1.5-4 motor but produced no significant differences in performance.

(U) Parameters measured included chamber pressure, burn rate, action time, mass flow rate, expansion ratio, throat and exit diameter, propellant weight and specific impulse corrected to zero degree divergence angle, 1000-psi chamber pressure expanded to 14.7 psi.

(U) No attempt was made to determine particle sizes in the exhaust or actual heat losses experienced in the motors. The theory which supports

Figure 2. Micromotor with Firing Head and Pressure Transducer Arrangement Used in Initial Phase of Program.

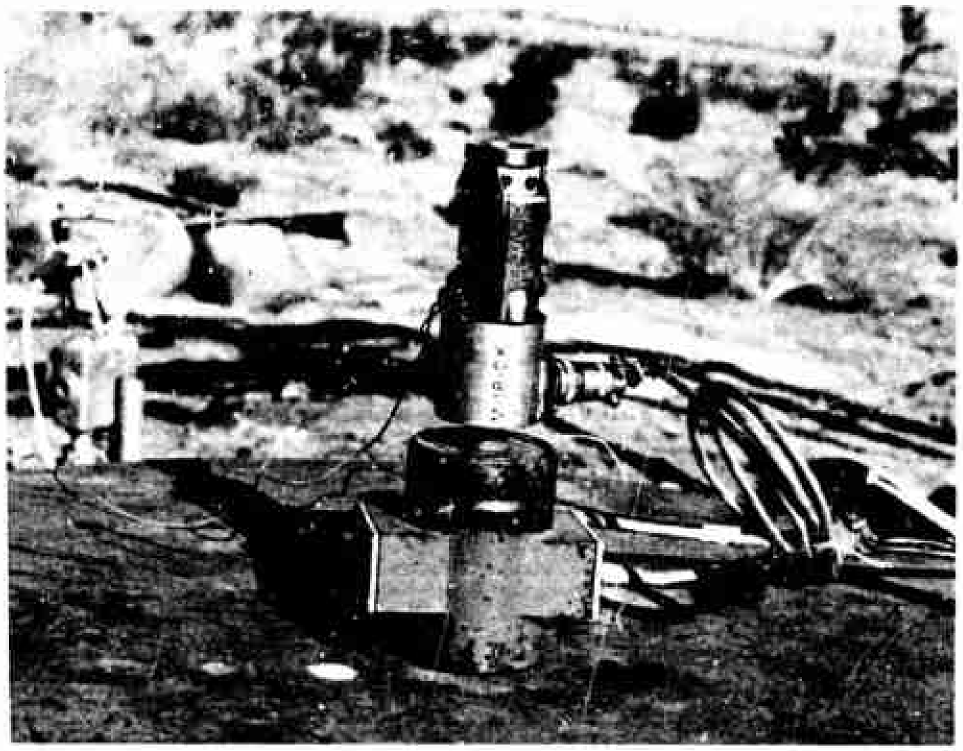

Figure 3. Micromotor with Firing Head Used in Latter Phase of Program - Pressure transducer is located in the head. This head was designed by Rohm and Haas Company, Redstone Arsenal Research Division, Huntsville, Alabama.

this scaling technique takes into account the effects of these phenomena by use of a formula which is given in a later section.

(U) Two-phase-flow calculations were based on a computer program used by Rohm and Haas(3). Ballistic data plus two-phase-flow loss values were then used to determine effective heat loss for the propellant according to the following equation:

$$q = \frac{\left(F^{o}_{1000}\right)_2^2 - \left(\frac{1 - X\Delta_2}{1 - X\Delta_1}\right)_2^2 \left(F^{o}_{1000}\right)_1^2}{\frac{2J\eta}{144g_o}\left[\left(\frac{1 - X\Delta_2}{1 - X\Delta_1}\right)\left(\frac{t_z A}{m}\right)_1 - \left(\frac{t_z A}{m}\right)_2\right]} \qquad (1)$$

Subscript. 1 and 2 denote motor 1 or 2 of the pair under consideration. The assignment of subscript is arbitrary.

A Δ value in the above equation is selected, for each of several effective particle sizes, N, from the previously cited computer program.

(U) A curve is thus generated of q versus N for each pair of motors. The point of intersection of the curves gives the values of effective heat flux and effective particle size. This value for q is then used in equation 2 to predict specific impulse in a large motor:

$$\left(F^{o}_{1000}\right)_2 = \sqrt{\left(\frac{1 - X\Delta_2}{1 - X\Delta_1}\right)^2 \left[\left(F^{o}_{1000}\right)_1^2 + \frac{2J\eta q}{144g_o}\left(\frac{t_z A}{m}\right)_1\right] - \frac{2J\eta q}{144g_o}\left(\frac{t_z A}{m}\right)_2} \qquad (2)$$

(U) Propellant for the reported series was mixed and cast into motors in a deliberately random order. Firings were also conducted in a random order.

(U) Prediction of specific impulse in a large motor cannot be made without knowledge of the motor configuration including: action time, area of exposed internal hardware, propellant weight, and Δ. These parameters are required for equation 2 above.

(U) In addition, extrapolations to large motor impulse should not be made using a reference propellant in micromotors and a different propellant in a large motor. Biased results will almost certainly occur.

(U) Finally, since two-phase-flow losses and particle sizes are not measured, the entire approach may be questioned, as these effects are considered to play a large part in predicting large motor impulses. However, for the two propellant series attempted thus far, results have been promising. Should future testing indicate that this technique does not give valid results, a method would be sought which measured heat loss and particle size. One such approach is the BATES program[4], used by the Solid Rocket Division, Air Force Rocket Propulsion Laboratory. This method measures the above parameters in addition to the more easily obtained ballistic parameters.

(U) The author believes that with careful consideration of the variables affecting the ballistic results, a reasonably accurate prediction can be made as a guide to the potential of a new propellant formulation.

SECTION III

INSTRUMENTATION

(U) Data from firings were obtained from strain-gage pressure transducers and a dual-bridge strain-gage load cell, and recorded on a Systems Electronics Laboratory Model 600 data-acquisition system. Quick-look oscillograph data were available from a Consolidated Electronics Corporation oscillograph, and some reduced results were available from a SEL 810A computer which is located at the test site.

(U) No filters were used to eliminate thrust oscillations. Transducers were calibrated to $\pm 0.25\%$ accuracy. Overall accuracy of the acquisition system was $\pm 0.16\%$ end-to-end.

SECTION IV

DATA REDUCTION

(U) The data reduction procedure used within this Laboratory for solid propellant ballistic data was adapted from that used by the Rohm and Haas Company, Redstone Arsenal Research Division, Huntsville, Alabama. The only changes made in the program were those required to run the program on the IBM 7040 computer, in use at AFRPL. In addition, the integration of values for Isp is made from zero to zero rather than the 10% to 10% values which are common at many facilities. The noise level of instrumentation at the Propellant Evaluation Facility is low enough to permit accurate determination of deviation from zero values.

SECTION V

RESULTS

(U) Twenty-six firings were made to obtain the data for the CMDB propellant. These data are summarized in Tables II, III, and IV. Burn-rate data are for actual chamber pressures and are not corrected to 1000 psi.

(C) Table II. Summary of Ballistic Results - .75C.50-1.5 Motor (RH-P-112 Propellant)

Isp (del)	I^o_{1000} (lbf-sec/lbm)	C*	Mass Flow (lb/sec)	K_n	Burn Rate (in./sec)	Action Time (sec)	Ave P_c
230.0	232.2	4912	0.076	171	0.729	0.271	1083
230.9	233.5	5244	.104	157	.709	.195	1038
229.7	233.8	4947	.104	170	.692	.200	982
234.0	235.7	4839	.107	172	.727	.193	1088
232.8	235.2	4780	.112	172	.779	.185	1138
232.0	234.3	4805	.115	170	.736	.180	1089
238.5	240.1	4829	.112	173	.760	.186	1145
228.1	232.4	4849	.100	162	.662	.206	979
230.4	234.6	4864	.100	160	.658	.207	925
Mean Values							
231.8	234.6	4897	.103	167	.717	.203	1052
σ - Standard Deviation							
2.9	1.6	147	.011	6	.040	.027	61

(C) Table III. Summary of Ballistic Results - .75C.50-3.5 Motor (RH-P-112 Propellant)

Isp (del)	I^o_{1000} (lbf-sec/lbm)	C^*	Mass Flow (lb/sec)	K_n	Burn Rate (in./sec)	Action Time (sec)	Ave P_c
236.9	237.6	5023	0.279	170	0.768	0.178	1158
238.4	239.1	4807	.271	175	.776	.178	1149
236.5	239.3	4969	.245	168	.843	.199	1081
238.0	240.0	4985	.273	163	.742	.182	1061
233.3	236.7	5017	.228	165	.834	.208	1039
238.9	239.3	5051	.278	172	.769	.178	1178
236.9	238.6	4967	.247	170	.780	.199	1122
236.8	239.4	5053	.262	161	.756	.189	1060
Mean Values							
237.0	238.8	4984	.260	168	.784	.189	1106
σ - Standard Deviation							
1.7	1.1	42	.018	5	.028	.003	47

(C) Table IV. Summary of Ballistic Results - 2C1.5-4 Motor (RH-P-112 Propellant)

Isp (del)	I^{o}_{1000} (lbf-sec/lbm)	C^*	Mass Flow (lb/sec)	K_n	Burn Rate (in./sec)	Action Time (sec)	Ave P_c
239.8	242.7	5032	0.806	149	0.726	0.370	985
239.8	243.7	4953	.774	150	.712	.383	956
242.5	242.6	4979	.861	163	.785	.347	1157
241.1	243.6	5012	.775	151	.740	.383	1013
238.0	241.0	5007	.817	148	.748	.362	990
241.8	244.1	5050	.829	149	.749	.359	1023
242.6	243.0	4854	.846	161	.781	.350	1147
236.8	240.9	4862	.783	151	.719	.376	947
238.8	241.7	4968	.811	153	.733	.367	999
Mean Values							
240.1	242.6	4969	.811	153	.744	.366	1024
σ - Standard Deviation							
1.9	1.2	78	.031	5	.026	.013	76

(U) From these data, q values were obtained with equation 1 and plotted in Figure 4.

(U) With these parameters calculated, a prediction was made for specific impulse in a 6C5-11.4 motor using equation 2. This motor is 6 inches in diameter with 1/2-inch web thickness, and is 11.4 inches long. Grain weight is nominally 6 pounds. This motor produces 2500 pounds thrust at 1000-psi chamber pressure, and a mass flow of 8.5 lb/sec.

(U) The predicted value from equation 2 was 244.5 lbf-sec/lbm. The average value from four firings, as shown in Table V, was 245.8 lbf-sec/lbm. This is a difference of 1.3 lbf-sec/lbm, or 0.5%, from the predicted value.

(C) Table V. Summary of Ballistic Results - 6C5-11.4 Motor (RH-P-112 Propellant)

Isp (del)	I^{o}_{1000} (lbf-sec/lbm)	C^*	Mass Flow (lb/sec)	K_n	Burn Rate (in./sec)	Action Time (sec)	Ave P_c
243.9	245.2	5020	8.327	157	0.816	0.703	1113
245.1	245.2	5003	8.747	158	.827	.673	1169
243.9	245.3	5001	9.936	158	.800	.697	1090
239.2	247.6	4996	7.280	130	.711	.779	804
Mean Values							
243.0	245.8	5005	8.573	150	.789	.713	1044
σ - Standard Deviation							
2.6	1.2	10	1.099	13	.030	.011	140

(U) A prediction was also made, in the same manner, for a nominal 70-pound BATES motor. The predicted value of I^{15}_{1000} was 242.8 lbf-sec/lbm. The reported value(5) is 241.6 lbf-sec/lbm. The difference is 1.2 lbf-sec/lbm, or 0.5%, from the predicted value. The "known" data used in equation 2 were based on the 2C1.5-4 motor with a nominal grain weight of one-fourth pound.

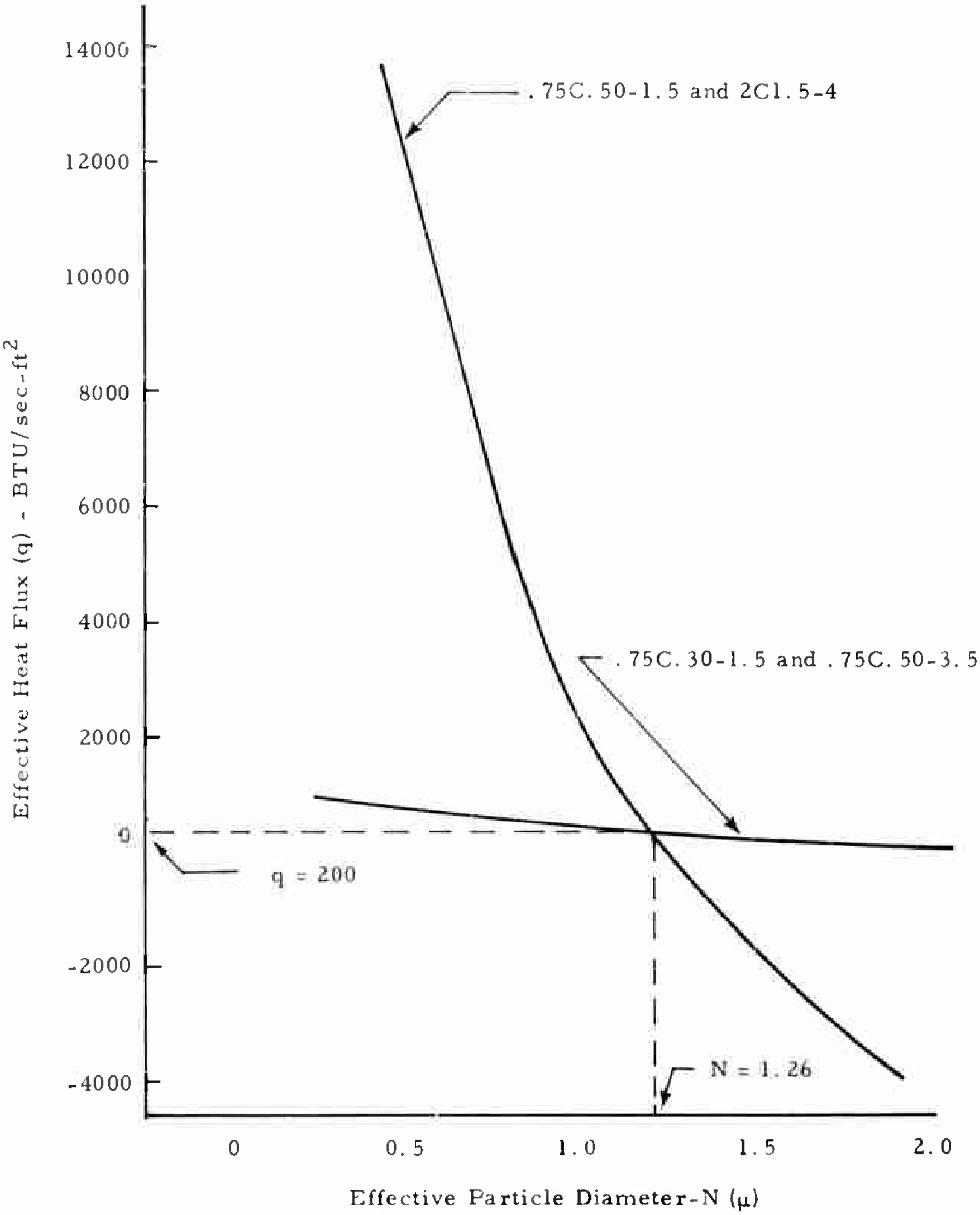

Figure 4. q-N Curves for Scaling Factor Determination with RH-P-112.

(U) As a further check of the technique, a similar series was run using TP-H-1011 propellant on the same motor configurations. These data are summarized in Tables VI, VII, and VIII.

(C) Table VI. Summary of Ballistic Results - .75C.50-1.5 Motor (TP-H-1011 Propellant)

Isp (del)	I^{o}_{1000} (lbf-sec/lbm)	C*	Mass Flow (lb/sec)	K_n	Burn Rate (in./sec)	Action Time (sec)	Ave P_c
217.9	233.0	4994	0.048	203	0.323	0.453	591
219.4	234.7	4979	.046	210	.324	.491	593
196.1	219.5	4414	.039	185	.332	.495	488
206.1	225.2	4547	.043	197	.316	.474	503
197.3	223.8	4680	.040	168	.308	.509	416
192.4	219.7	4281	.038	180	.301	.483	411
216.3	235.4	4901	.044	208	.292	.509	520
210.3	231.8	4747	.037	204	.296	.569	493
220.7	235.8	4884	.050	212	.317	.455	595
Mean Values							
208.5	228.8	4714	.043	196	.312	.493	512
σ - Standard Deviation							
11.0	6.7	255	.005	15	.001	.035	71

(C) Table VII. Summary of Ballistic Results - .75C.50-3.5 Motor (TP-H-1011 Propellant)

Isp (del)	I^{o}_{1000} (lbf-sec/lbm)	C^*	Mass Flow (lb/sec)	K_n	Burn Rate (in./sec)	Action Time (sec)	Ave P_c
234.3	233.7	4224	0.099	502	0.667	0.535	1749
234.1	240.4	5034	.123	259	.379	.409	864
229.2	240.0	5112	.120	216	.339	.420	677
232.6	234.6	5019	.130	303	.409	.397	1092
226.2	231.9	4944	.081	339	.559	.639	1167
235.4	237.7	5064	.113	319	.388	.450	1081
231.7	236.9	5171	.103	283	.357	.470	903
238.3	238.6	5042	.120	345	.398	.439	1258
Mean Values							
232.7	236.7	4951	.111	321	.437	.470	1099
σ - Standard Deviation							
3.5	3.1	141	.015	79	.107	.076	320

(C) Table VIII. Summary of Ballistic Results - 2C1.5-4 Motor (TP-H-1011 Propellant)

Isp (del)	I^o_{1000} (lbf-sec/lbm)	C*	Mass Flow (lb/sec)	K_n	Burn Rate (in./sec)	Action Time (sec)	Ave P_c
228.6	239.7	4735	0.346	229	0.337	0.797	701
230.4	238.4	4686	.381	256	.352	.805	786
234.2	239.9	4875	.344	269	.332	.849	867
232.4	237.7	4977	.276	291	.340	.999	897
233.8	239.2	4768	.376	269	.350	.750	862
234.2	237.4	4785	.365	301	.363	.835	974
224.3	236.5	4643	.277	235	.348	.879	636
237.3	238.5	4981	.394	304	.380	.764	1098
Mean Values							
231.9	238.4	4806	.345	269	.350	.835	859
σ - Standard Deviation							
3.0	1.2	127	.045	28	.015	.079	137

(C) From these data, q values were calculated for TP-H-1011. These values are plotted in Figure 5.

(C) Having obtained a value for q and N, a prediction was made for specific impulse in a 6C5-11.4 motor using equation 2. The predicted value was 246.2 lbf-sec/lbm. The average value from three firings, Table IX, was 244.8 lbf-sec/lbm. The difference is 1.4 lbf-sec/lbm, or 0.57% from the predicted value.

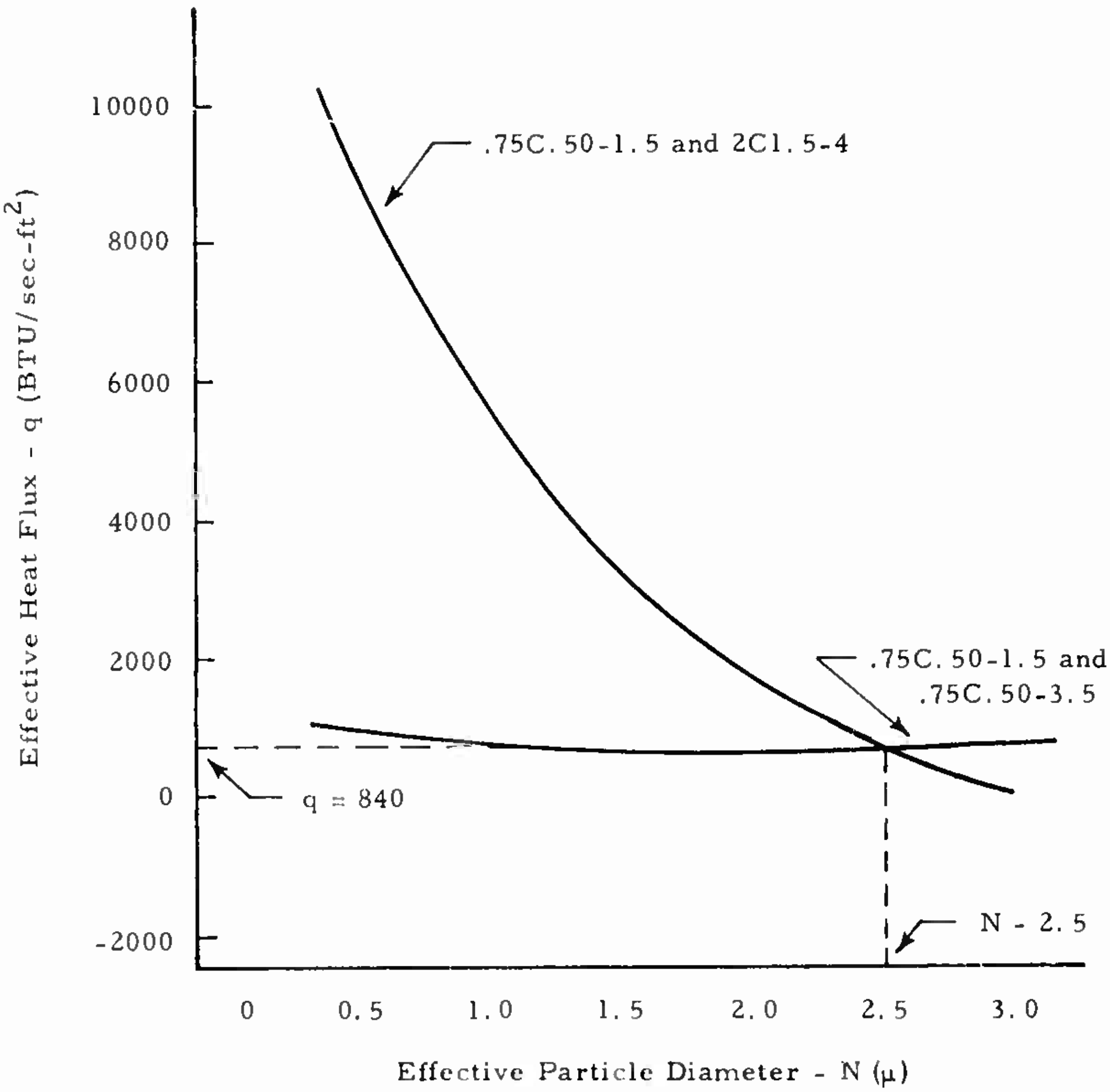

Figure 5. q-N Curves for Scaling Factor Determination with TP-H-1011.

(C) Table IX. Summary of Ballistic Results - 6C5-11.4 Motor (TP-H-1011 Propellant)

Isp (del)	I^o_{1000} (lbf-sec/lbm)	C*	Mass Flow (lb/sec)	K_n	Burn Rate (in./sec)	Action Time (sec)	Ave P_c
233.3	247.2	4892	2.749	227	0.362	1.741	717
237.7	245.0	4977	3.391	276	.455	1.846	989
239.4	244.8	4932	3.725	269	.386	1.668	934
Mean Values							
236.8	245.7	4934	3.288	257	.401	1.752	880
σ - Standard Deviation							
3.1	1.3	43	.496	27	.050	.089	144

(C) A prediction was made for a 70-lb BATES grain using TP-H-1011. The predicted value was 244.8 lbf-sec/lbm, and the delivered value was 243.2 lbf-sec/lbm. This is a difference of 1.6 lbf-sec/lbm, or 0.66%.

(U) The difference between predicted and delivered values of specific impulse is well within the limits of experimental error. The advantages of this method of impulse prediction are (1) it is quick and simple, utilizing no special measuring equipment other than that required for normal ballistic evaluation of small solid propellant rocket motors, and (2) the entire evaluation may be made with as little as 2 pounds of propellant. This is especially important with many new ingredients that are available in very limited quantities.

SECTION VI

ERRORS AND LIMITATIONS

(U) One of the common causes of unreliable data is erroneous measurement of variables. Erroneous measurements may be imprecise, inaccurate or both because of random errors, determinate errors or both. In this evaluation, far more effort than normal was made to determine the precision and accuracy of the measurements. Multiple measurements, statistical analyses, careful attention to all aspects of instrumentation and constant surveillance were used to measure and eliminate errors.

(U) The results of these efforts have been partially discussed in the results section. The author believes that the precision of the data is well within acceptable limits. The accuracy of the data is not as well established as the precision.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

(C) The specific impulse scaling program as developed by Rohms and Haas and adapted at AFRPL is a good technique for predicting the performance of candidate propellant ingredients in large solid motors. This technique was found to provide good prediction of performance through 70-pound BATES grain size using RH-P-112 composite double-base propellant and the composite rubber base TP-H-1011. This prediction technique does not include the effects of nozzle geometry, therefore, this technique would not be directly appropriate for predicting the performance of the TP-H-1011 propellant in the four-nozzle Minuteman (M-55) motor.

(U) The feasibility of this technique has been demonstrated. The technique will be used in future efforts to determine the specific impulse of solid propellant combinations of both research and engineering development programs of interest to the Air Force Rocket Propulsion Laboratory.

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5. Solid Propellant Rocket Static Test Working Group, 4th Meeting Bulletin, CPIA Publication No. 124 Vol. II, December 1966.

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13. ABSTRACT

A technique developed by the Rohm and Haas Company for specific impulse scaling has been adapted for use at the Air Force Rocket Propulsion Laboratory. The purpose of this technique is to predict specific impulse in large solid rocket motors based on data obtained in micromotors. As little as 2 pounds of propellant are required to obtain the data from which the prediction is made. The technique has been checked with a composite-modified-double-base propellant and a polybutadiene composite propellant. Within the limitations described, this technique can provide useful information concerning performance of a propellant in a large solid motor. Predictions, based on data obtained in micromotors, were within 0.6% of the delivered impulse in 6-pound motors and 70-pound BATES motors. (U)

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